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Self-healing in cementitious materials: Materials, methods and service conditions

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ABSTRACT

In this paper, mechanisms of self-healing in cementitious materials, i.e. autogenous self-healing, self-healing based on mineral admixtures, self-healing based on bacteria and self-healing based on adhesive agents, are reviewed. Literature shows that all mechanisms of self-healing are effective, to some extent, under some particular conditions. It reveals that not any particular method of self-healing is the best, but one can be the most suitable for a particular situation. For better application of self-healing concept in engineering practice, favorable situations for self-healing in cementitious materials are summarized. The required environmental conditions for each self-healing mechanism are analyzed. Additional costs for realizing self-healing in concrete structures are also discussed. Based on the aforementioned aspects of self-healing in cementitious materials, perspectives for further research on application of self-healing in engineering practice are proposed.

1. Introduction

Concrete is a brittle composite cementitious material that easily fractures under tensile loading. For this reason, reinforcement is installed in order to carry the tensile cross sectional forces after cracking. From this point of view, reinforced concrete is always designed to allow the occurrence of cracks. Cracks as such are not regarded as failure of reinforced concrete as long as a prevailing crack width criterion is not exceeded [1]. However, they provide preferential accesses for aggressive agents, such as chlorides, sulfates and carbonates. These aggressive agents can not only induce corrosion of reinforcement steel, but also degrade the concrete. Thus service life of reinforced concrete structures is shortened. In addition, cracks cause leakage in concrete structures, such as water reservoirs, roofs and water pipes, and negatively affects their functionality.

For solving the aforementioned service life and leakage problems caused by cracks, man-made repair is a common solution [2]. Although man-made repair can prolong service life of reinforced concrete structures, it has some limitations. For instance, the cost of man-made repairs are usually very high [3]. Moreover, if structures, like bridges and tunnels, have to be taken out of service for repair, the indirect costs are generally several times higher than the direct costs [2]. Apart from the high cost of repair, it is recognized that realizing durable repairs is difficult, even though the quality of such repairs has substantially increased in recent years. Most of these repairs can only last for ten to fifteen years [2]. Furthermore, it is difficult to repair cracks which are not accessible, such as the cracks in underground concrete structures [4].

In comparison, self-healing of cracks in concrete structures could be beneficial [4]. Self-healing of crack blocks the crack pathway and, therefore, prevents from water leakage. Functionality of the concrete structures is regained. At the same time, block of crack pathway due to self-healing inhibits ingress of aggressive ions. As a result, service life of concrete structures is prolonged. Moreover, self-healing of crack increases abrasion between crack surfaces and, therefore, restores compressive strength of the cracked concrete matrix [5]. Similarly, self-healing of damages at interfaces between fibers and cementitious matrix can restore mechanical properties of fiber reinforced concrete. Therefore, it is significant to make reinforced concrete structures smart enough to detect their own damage and repair themselves [6].

As a novel idea, self-healing of cracks has attracted much attention worldwide in recent years and some reviews on self-healing have been published, mainly focusing on healing agents and methods to evaluate the efficiency of self-healing [6–10]. In this paper, different mechanisms of self-healing in cementitious materials and the corresponding healing agents were reviewed. For better application of self-healing concept in engineering practice, favorable situations for self-healing in cementitious materials are summarized. The required environmental conditions for each self-healing mechanism are analyzed. The costs due to the addition of self-healing agents are also discussed. Based on the aforementioned aspects of self-healing in

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cementitious materials, perspectives for further research on application of self-healing in engineering practice are proposed.

2. Mechanisms of self-healing and required conditions

Based on the literature survey, self-healing of cracks in cementitious materials can be grouped into four categories according to mechanisms:

1) autogenous self-healing,
2) self-healing based on mineral admixtures,
3) self-healing based on bacteria,
4) self-healing based on adhesive agents.

The physico-chemical healing process, influencing factors, advantages and disadvantages of these categories of self-healing are described in this section.

2.1. Autogenous self-healing

2.1.1. Phenomena of autogenous self-healing and its effect

Autogenous self-healing in Portland cement concrete has attracted much attention since it was observed many years ago. According to Hearn [11], the phenomena of autogenous self-healing had already been noticed in water retaining structures, culverts and pipes by Hyde [12] by the end of nineteenth century. In 1920s, a more systematical analysis of autogenous self-healing was reported by Glanville [13]. After that, autogenous self-healing of cracks in concrete bridges was also investigated [14,15].

The effect of autogenous self-healing on water leaking through cracks was extensively studied by Clear [16], Hearn [17] and Edvardsen [18]. Moreover, Reinhardt et al. [19] correlated this effect with different temperatures and crack widths. The reduction of chloride ingression through cracks due to autogenous self-healing was reported by Fidjestol et al. [20], Ramm et al. [21] and Otsuki et al. [22]. Apart from the durability aspect, the improvement of mechanical properties of concrete due to autogenous self-healing has been explored as well. Lauer and Slate [23] demonstrated that the tensile strength measured perpendicular to the crack plane increased after autogenous self-healing of cracks. In that study, the influence of age and curing conditions were also taken into account. Similarly, the recovery in strength of concrete was also found by Dhir et al. [24], Granger et al. [25] and Ferrara et al. [5].

2.1.2. Reaction products of autogenous self-healing

Although the effects of autogenous self-healing have been investigated for many years, reaction products of autogenous self-healing detected by researchers are not consistent. Jacobsen and Sellevold [26] found some newly formed C–S–H, portlandite and ettringite in cracks in high performance concrete that had suffered from frost deterioration and was cured in water for 3 months (under exposure to atmosphere). Schlangen and Ter Heide [27] detected newly formed C–S–H in cracks after the cracked samples were cured in unsealed water reservoir for 56 days. They concluded that autogenous self-healing was caused by further hydration of unhydrated cement clinker.

Edvardsen [18] found calcium carbonate ($CaCO_3$) in cracks after autogenous self-healing. Investigations by Yang et al. [28] and Qian et al. [29] also confirmed the existence of $CaCO_3$ in cracks. According to Edvardsen [18], when CO_2 in the air dissolves in water, CO_3^{2-} ions diffuse into cracks through the crack mouth. $CaCO_3$ precipitates in cracks when the concentration of Ca^{2+} and CO_3^{2-} ions reach supersaturation level (see Fig. 1 from [18]). However, Sisomphon [30] reported that, since the concentration of CO_3^{2-} nearby the crack mouth is higher than that inside the cracks, $CaCO_3$ tends to precipitate nearby the crack mouth (see Fig. 2 from [30]). Parks et al. [31] got a similar conclusion demonstrating that calcite was not detected in cracks in internal concrete.

Huang [32] characterized reaction products of autogenous self-healing under sealed conditions by means of EDS, TGA and FTIR. They found that the main components of reaction products formed in cracks in Portland cement paste with w/c ratio of 0.3 were portlandite and C–S–H. The portlandite accounted for almost 80% by mass of the reaction products. It indicates that not only further hydration of unhydrated cement is responsible for autogenous self-healing, but also the recrystallization of portlandite leached from the bulk paste.

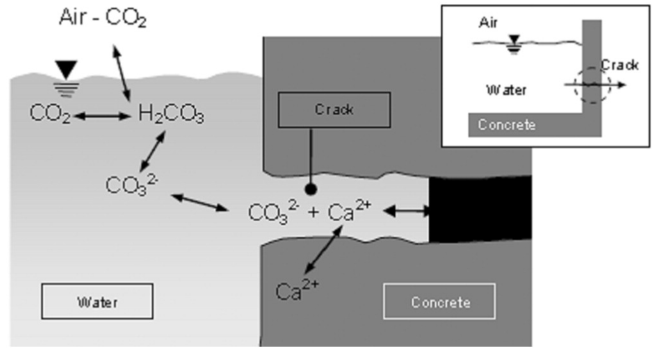

Fig. 1. Autogenous self-healing due to precipitation of calcium carbonate in the presence of water and dissolved CO_2 [18].
The figure was reprinted from [9].

2.1.3. Mechanisms of autogenous self-healing

By summarizing the aforementioned information, it can be found that the main mechanisms of autogenous self-healing could be:

(1) further hydration of unhydrated cement;
(2) recrystallization of portlandite leached from the bulk paste;
(3) formation of calcite.

All these physic-chemical processes can proceed simultaneously, but their rates are different. Further hydration of unhydrated cement at crack surfaces can take place immediately after water penetrates into cracks, while recrystallization of portlandite and formation of calcite proceed very slowly. Usually there are very few CO_3^{2-} ions existing in the bulk paste. In this case, calcite is hardly formed. However, CO_3^{2-} ions in cracks can come from outside environment, although the diffusion of CO_3^{2-} ions in water is very slow [33]. A gradient of CO_3^{2-} ion concentration is formed within the cracks. It is conceivable that concentration of CO_3^{2-} ions nearby the crack mouth is higher than that inside the crack. As a result, calcite is formed first nearby the crack mouth, as observed by Sisomphon [30]. As self-healing proceeds, more and more CO_3^{2-} ions reach the locations inside the cracks. The

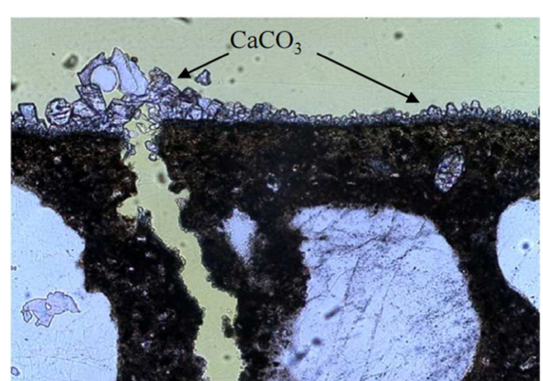

Fig. 2. Experimental evidence for preferential precipitation of calcium carbonate nearby the crack mouth [30].